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Estimating future diameters of lodgepole pine trees

Dennis M. Cole and Albert R. Stage

INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

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U. S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

The authors

DENNIS M. COLE is an Associate Research Silviculturist working on research in the silviculture of lodgepole pine, stationed at Bozeman, Montana. His studies have been primarily concerned with the description and management of growth and yield relationships of lodgepole pine forests.

ALBERT R. STAGE is Principal Mensurationist working on timber measurement and management planning, stationed at the Forestry Sciences Laboratory in Moscow, Idaho. His studies have included research on forest growth, yield, and site quality, as well as on sampling methods and inventory design.

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Abstract

Periodic diameter growth of lodgepole pine trees in Montana, Idaho, and Utah can be estimated by equations developed in this study. Use of these equations for estimating future diameters of individual trees is described for several combinations of tree and stand conditions.

Introduction

Management planning for timber production commonly states its goals in terms of tree size at harvest. Tree size, especially diameter at breast height (d.b.h.), has become an increasingly important element of such planning. In addition, tree size influences the quality and production costs of timber products and the biological and esthetic character of growing stands.

Growth and yield information is grossly inadequate for lodgepole pine (*Pinus contorta* Dougl.) in Montana, Idaho, and Utah, although results from some studies in surrounding areas may be extrapolated to fill immediate needs for approximate data on volume yields per acre (Dahms 1966; Myers 1967). The development of tree size has not been studied as intensively as stand growth and volume yield; therefore, such studies hold great promise for refining growth and yield estimates.

The purpose of this paper is to report the development of equations for predicting future tree diameters at breast height for lodgepole pines in Montana, Idaho, and northern Utah. A related report[1] describes a stand growth prognosis program that uses growth equations like the ones in this report to synthesize the development of stands.

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[1] A. R. Stage. A model for the prognosis of forest stand development. Intermountain Forest and Range Experiment Station. (In preparation.)

Methods

In 1969, measurements were taken on 264 lodgepole pine trees growing within 88 permanent sample plots established between 1957 and 1960. The plots represented a wide range of growing conditions in unmanaged, even-aged lodgepole pine stands over an extensive geographic area from northeastern Utah to northwestern Montana (fig. 1).

Three trees of differing crown class were randomly selected from each plot for individual-tree measurements. Measurements included total height, height to crown base, d.b.h., age at breast height, and 10-year radial increment. The crown base was "visually balanced" to determine measuring point, and radial increment was determined as the average of two increment core measurements taken at breast height. Cores were extracted at 180° to each other, on the average diameter as located by tree calipers.

Diameter-class tallies of the permanent plots furnished stand data at the time of establishment and again in 1969. Stand values, such as number of trees per acre and basal area, were linearly interpolated or extrapolated to 1959, so they would correspond to the beginning of the growth period measured on increment cores.

Increment of individual trees was analyzed both as radial increment, inside bark, and as increment in basal area, inside bark. In addition, a logarithmic transformation of each was used. To determine the most appropriate form of the dependent variable, a large set of independent data from management planning inventories and Forest Survey locations was utilized, employing Furnival's (1961) "Index of Fit" criterion. On this basis, the logarithm of basal area increment was found to be the superior form of the dependent variable.

Linear equations of the form $Y = b_0 + b_1X_1 + b_2X_2 + \ldots b_nX_n$ were then fitted to our data and subjected to screening to determine the equations of best fit, where Y represented the natural logarithm of basal area increment in square inches. Data were analyzed using Grosenbaugh's (1967) Rex-Fortran IV system for combinatorial screening and analysis of multivariate regressions.

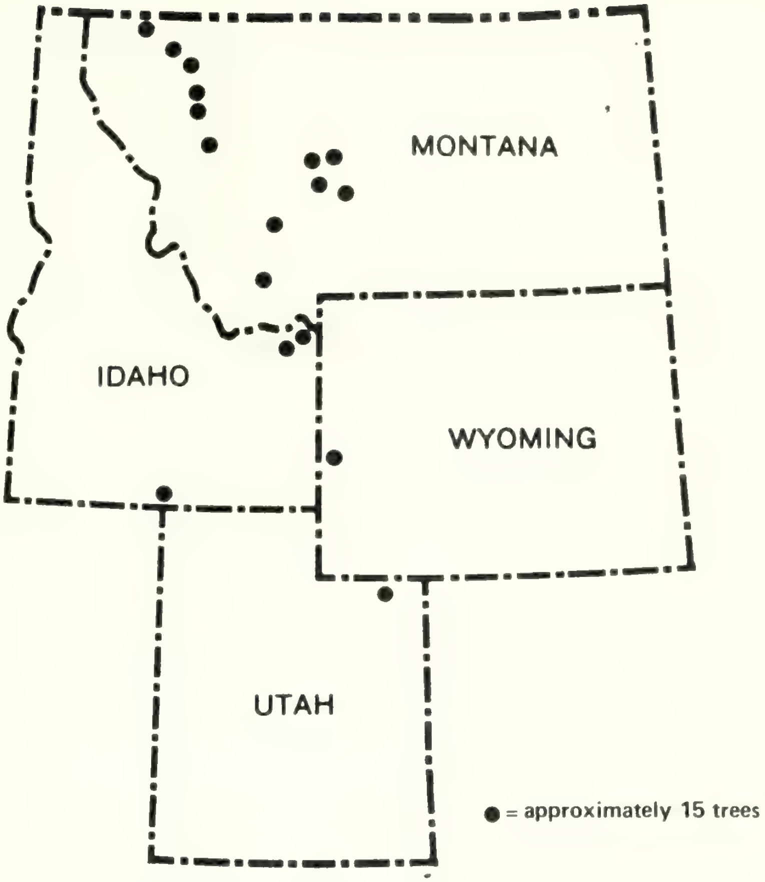

Figure 1.--Geographical distribution of sample trees.

To allow estimation of periodic basal area increment of individual trees in both managed and unmanaged stands, screenings were conducted only with prediction variables appropriate to each situation. Variables, or combinations of variables such as stand basal area and age, that would express past increment, were ruled out of the models that could apply to thinned stands. Although such variables would show a close correlation with subsequent increment, manipulation of stand density would change these variables so that the coefficients derived from our data would not apply.

Basic stand variables included in the analysis were lodgepole pine site index at 100 years--with corrections made for stand density (Alexander and others 1967), latitude, elevation, number of trees per acre, and basal area. Individual tree variables included were d.b.h., height, crown length, and age at breast height. Additionally, various other interaction terms and values derived from the measured variables were calculated and included in the analysis.

Crown competition factor (*CCF*) (Krajicek and others 1961) was calculated with the equation developed for lodgepole pine by Alexander and others (1967):

$$CCF = (0.00365 \overset{N}{\Sigma} D_i^2 + 0.01676 \overset{N}{\Sigma} D_i + 0.01925\ N)/A$$

where

D = D.b.h. of ith tree in plot

N = Number of trees in plot

A = Area in acres of plot

Equations for future growth estimation

In this study, as expected, the variable d.b.h. contributed most to future basal-area growth prediction. Simple correlation analysis showed the logarithm of d.b.h. to be highly correlated with the logarithm of subsequent 10-year basal-area growth of corresponding trees. The simple correlation coefficient was 0.74, corresponding to a coefficient of determination in simple linear regression which explained 55 percent of the variation in basal-area growth.

The addition of elevation, *CCF*, and the ratio of d.b.h. to average-stand-diameter ($d/\bar{D}$), raised to 76.4 percent the amount of variation accounted for (equation 2, table 1). As measures of stand competition effects and relative competitive status of the subject trees, respectively, the variables *CCF* and $d/\bar{D}$ make worthwhile contributions. In the presence of elevation, they explain approximately 3.5 percent more variation than did any other combination of three variables added to d.b.h.

In addition to the measure of relative competitive status afforded by $d/\bar{D}$, an indicator of tree vigor (crown ratio) was also tested for its contribution. However, because crown length measurements were not available at the beginning of the growth period, the test was made using all independent variables measured at the end of the growth period. The simple correlation coefficient between the logarithms of periodic basal area growth and crown ratio was 0.36; however, when added to the equation containing d.b.h., *CCF*, $d/\bar{D}$, elevation, and site index, crown ratio had virtually no effect--it raised explained variation by only 0.2 percent.

It appears that crown ratio is not a useful prediction variable for basal-area increment of individual trees in uniform, undisturbed stands of lodgepole pine when such measures as *CCF* and $d/\bar{D}$ are available.

Table 1.--*Equations for predicting future periodic basal-area growth of lodgepole pine trees*

Application	Equation No.	Basic variables[1]	Equations	Percent of variation accounted for	Standard error of estimate (% of mean)
A. Managed and unmanaged stands	1	$d, CCF, \overline{D}, EL, S$	Y[2] $= -2.0978 + 0.5297 \ln(d) - 0.9256 \ln(CCF) + 1.5728\, d/\overline{D} + 1.1814 \ln(S) + 0.0094\, EL$	80.3	63.4
	2	$d, CCF, \overline{D}, EL$	$Y = 3.4882 + 0.5575 \ln(d) - 0.9332 \ln(CCF) + 1.5274\, d/\overline{D} + 0.0018\, EL$	76.4	70.9
B. Unmanaged stands	3	$d, CCF, \overline{D}, EL, S, A$	$Y = -2.7670 + 1.4687 \ln(d) - 0.3998 \ln(CCF) + 0.8884\, d/\overline{D} + 39.3966/A + 0.3959 \ln(S) + 0.0054\, EL$	83.4	57.2
	4	$d, CCF, \overline{D}, EL, A$	$Y = -1.6837 + 1.6436 \ln(d) - 0.3068 \ln(CCF) + 0.7555\, d/\overline{D} + 46.4827/A + 0.0030\, EL$	83.1	57.6
	5	$d, CCF, \overline{D}, A$	$Y = -1.4497 + 1.6128 \ln(d) - 0.3137 \ln(CCF) + 0.7802\, d/\overline{D} + 46.0266/A$	82.9	57.8

---

[1] d = d.b.h. outside bark, in inches; CCF = crown competition factor; $\overline{D}$ = diameter of tree of mean basal area; EL = elevation above sea level in hundreds of feet; S = lodgepole pine site index (100-year base); A = tree age at breast height in years.

[2] Y = natural logarithm of 10-year basal area increment in square inches at breast height.

Addition of site index to the variables of equation 2 further raised the amount of variation accounted for to 80.3 percent (equation 1, table 1). With the exception of tree age, none of the other basic variables mentioned contributed appreciably to explained variation when in multiple regression with the variables presented in equations 1 and 2. Equations 1 and 2 are usable for future growth prediction in unmanaged stand situations. We also believe that equations 1 and 2 may be applied in managed stands as an interim guide under conditions where changes resulting from treatment or natural causes would be reflected in corresponding changes in measured values of d.b.h., *CCF*, and $d/\overline{D}$.

Age has been shown to be a significant variable in predicting past periodic diameter and volume growth of ponderosa pine (*Pinus ponderosa* Laws.) (Lemmon and Schumacher 1962) and past volume growth of lodgepole pine stands (Dahms 1966). To assess the effect of tree age on prediction of future basal area growth of individual lodgepole pine trees, the reciprocal of tree age at breast height was added to the variables involved in equations 1 and 2 of table 1. Equation 4, table 1, shows that an additional 6.7 percent of variation is accounted for by the inclusion of tree age with the variables of equation 2; but equation 3 reveals that the further inclusion of site index only accounts for an additional 0.3 percent of variation. It is interesting to compare this small addition to the 3.9 percent increase in explained variation that is accounted for by site index in the presence of the same variables without age as shown for equations 1 and 2. Apparently, in these undisturbed stands, d.b.h. and age indirectly represent the influence of site index on diameter growth to an extent that further inclusion of site index itself has little additional value in predicting basal area growth of individual trees. Lemmon and Schumacher (1962) reported a similar effect in regard to diameter growth prediction of ponderosa pine trees. Subsequent elimination of both site index and elevation from the equations including age resulted in a very small reduction in variation explained, as shown by equation 5, table 1, in comparison to equation 3. Hence, if age is to be measured, equation 5 gives virtually the same accuracy in prediction of basal area growth as do equations requiring the additional measurement of site index and elevation.

The usefulness of prediction equations containing age is limited by two factors. First, by the practical consideration of whether the value of the 2.6 percent increase in explained variation (equation 5 versus equation 1) offsets the additional expense of increment boring to obtain tree age. Second, tree age in the presence of d.b.h. indirectly functions as a past diameter growth rate and can be expected to be highly correlated with future growth rate unless stand growing conditions change significantly. Since a common objective of management is to increase growth rates, obviously the past growth rate implied by d.b.h. and tree age will not be representative of that expected to follow cultural operations. Accordingly, we do not recommend using these prediction equations involving age in disturbed stands, because no such stands were included in our data, and we doubt that the influence of age would be independent of past treatment.

In view of the high percentage of accounted-for variation, the reduction in increment boring, and its application to both managed and unmanaged stand situations, equation 1 seems most practical for predicting future basal area growth of lodgepole pine trees.

How to estimate future diameter

The Y's predicted in the equations of table 1 are the logarithms of the change in basal area, inside bark, for an individual tree. To use these growth values to estimate future diameter, the Y's must be converted to a change in diameter, outside bark.

Therefore, let

D_{ib} = diameter inside bark at end of decade

D_{ob} = diameter outside bark at end of decade

d_{ib} = diameter inside bark at start of decade

d_{ob} = diameter outside bark at start of decade

$\ln(x)$ = natural logarithm of x

$\exp(x)$ = exponential function of x

then

$$Y = \ln \{ (D_{ib}^2 - d_{ib}^2) \pi/4 \}$$

or

$$\exp(Y) = 0.7854 \, (D_{ib}^2 - d_{ib}^2)$$

$$D_{ib}^2 = d_{ib}^2 + 1.273238 \exp(Y)$$

and

$$D_{ib} = \sqrt{d_{ib}^2 + 1.273238 \exp(Y)}$$

To obtain future diameter outside bark (D_{ob}), the effect of bark growth must be approximated. This can be done by multiplying the above expression for basal area growth by the ratio of outside bark diameter to inside bark diameter. Then,

$$D_{ob} = \sqrt{d_{ob}^2 + (d_{ob}/d_{ib})^2 \ (1.273238 \exp (Y))}$$

In application, the user should measure a sample of bark thickness to establish the ratio. If direct measurement is not possible, the average value of the ratio for the trees in this study ($d_{ob}/d_{ib} = 1.077$) can be used.

The trends of diameter outside bark (D_{ob}) generated by repeated application of the above equation to values obtained from solving equation 1, for several combinations of site index, crown competition factor, and ratios of tree d.b.h. to diameter of tree of mean basal area ($d/\overline{D}$), are illustrated in figures 2 through 4 of the Appendix.

For a timespan of one decade, the curves are valid. For more than one decade, the curves are only approximate because they ignore any natural change in CCF or $d/\overline{D}$ that would be the consequence of growth and mortality among remaining trees in the stand. Changes in the stand variables can be considered only by imbedding these diameter growth equations in a stand growth simulation procedure.

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Appendix

To use the curves in the Appendix, find the graph for the desired *CCF* and $d/\overline{D}$. Move along the curve for the appropriate site index until the height of the curve corresponds to present d.b.h. Then move one decade interval to the right to find diameter one decade hence. Note that the horizontal axes are labeled "decade intervals" to indicate a discontinuity-over-time of the curve relationships shown. This has been done to prevent the graphs from being mistakenly interpreted as illustrating diameter growth development over age (or longer intervals of time than 10 years).

Users are reminded that these curves utilize site index values based on a 100-year index. The curves are for an average elevation of 6,000 feet above mean sea level. With regard to the effect on diameter increment, an increase of 1,000 feet in elevation would correspond to a decrease of about 8 percent in site index.

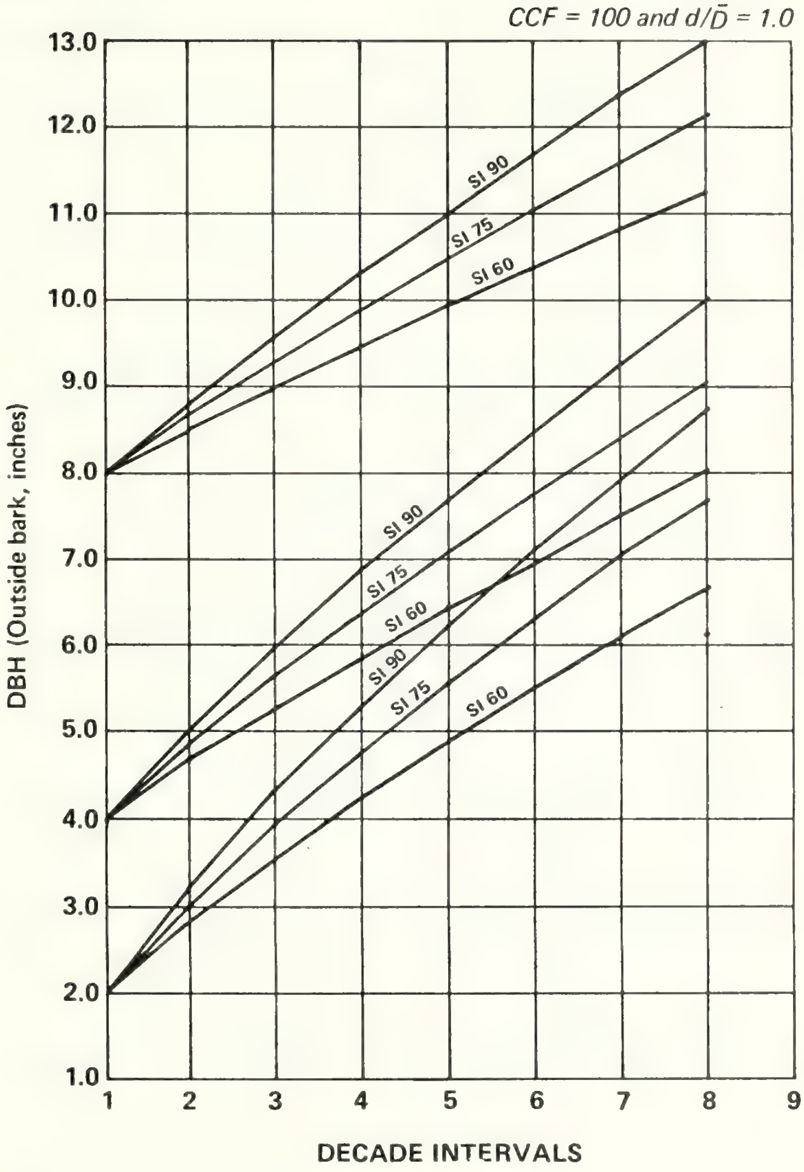


Figure 2a.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 100, and the ratio of tree d.b.h. to average stand d.b.h. ($d/\bar{D}$) = 1.0.

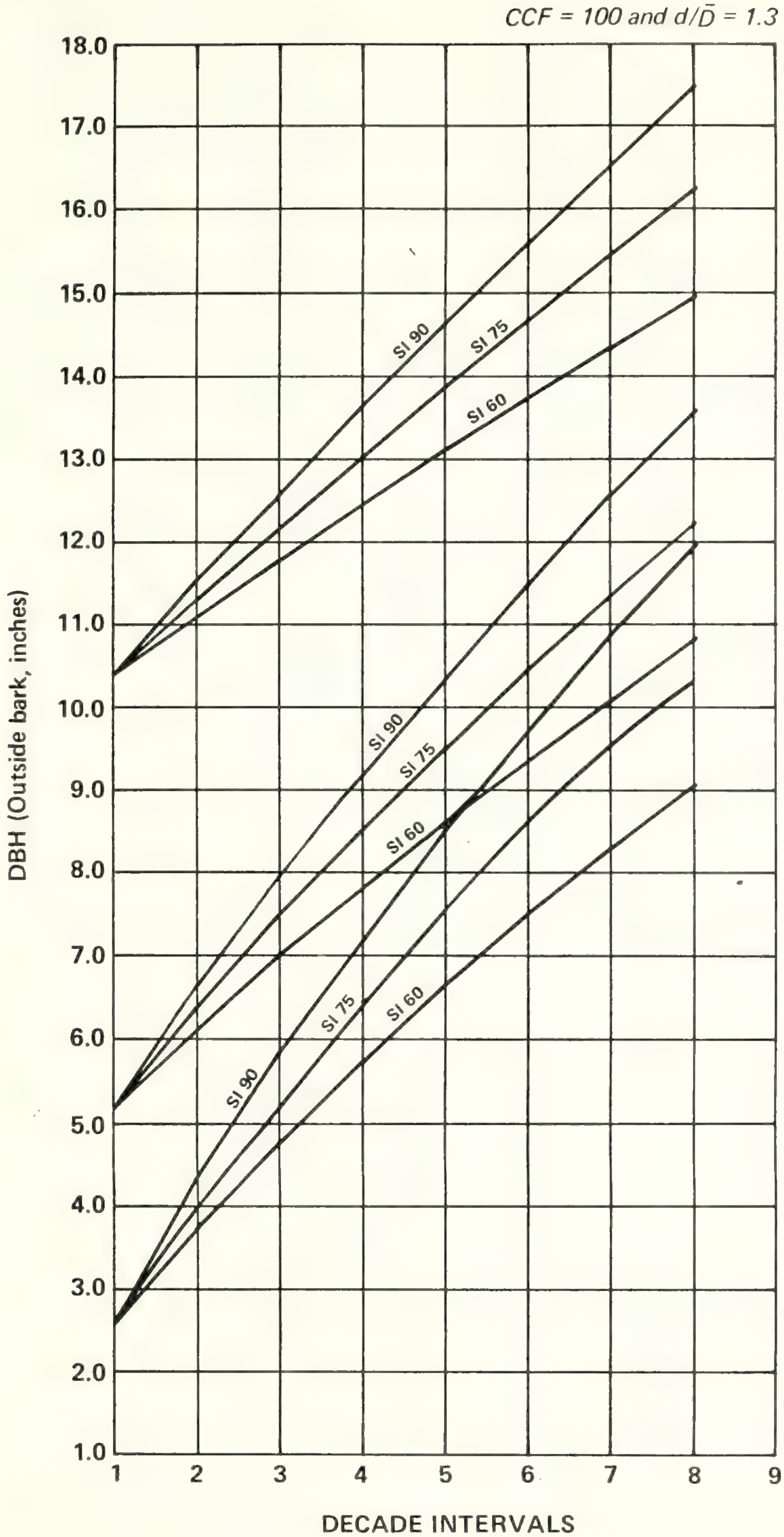


Figure 2b.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 100 and the ratio of tree d.b.h. to average stand d.b.h. (d/$\bar{D}$) = 1.3.

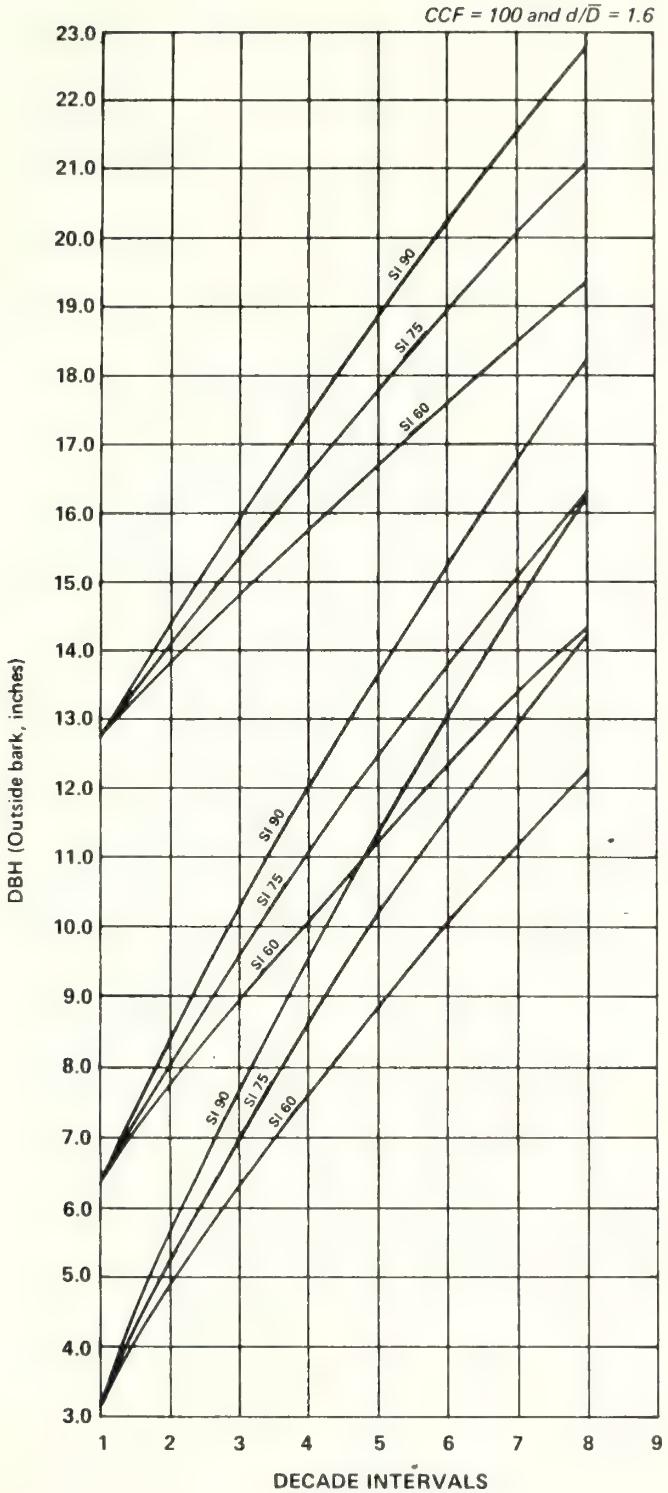


Figure 2c.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 100, and the ratio of tree d.b.h. to average stand d.b.h. ($d/\overline{D}$) = 1.6.

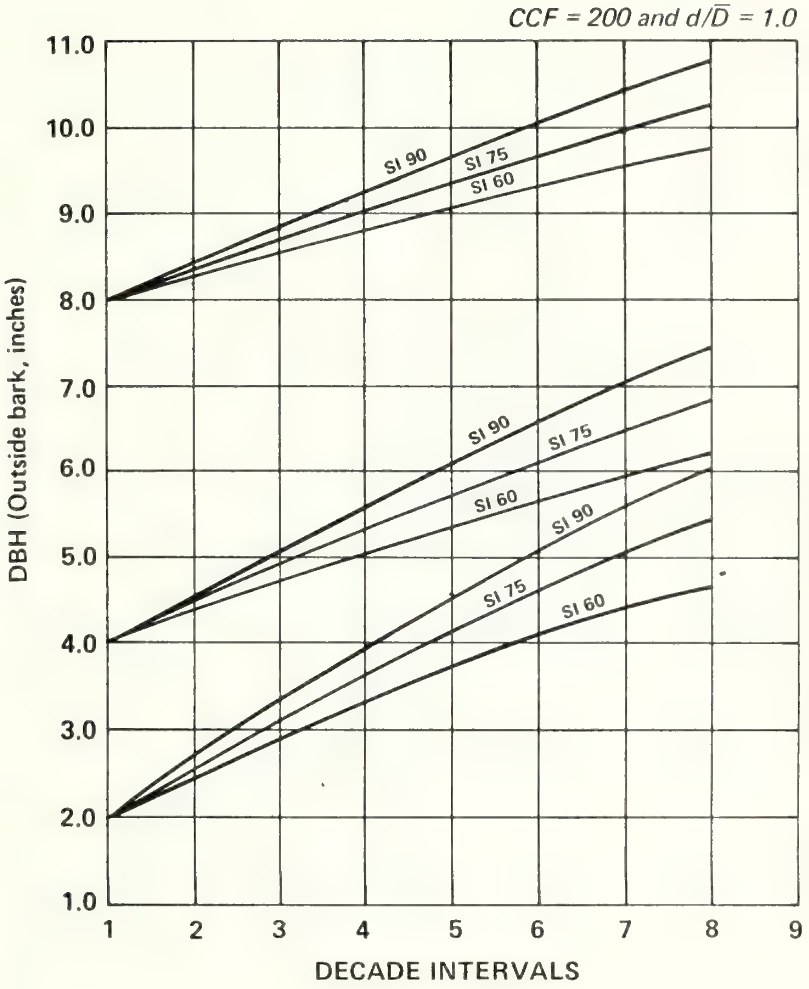


Figure 3a.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 200, and the ratio of tree d.b.h. to average stand d.b.h. ($d/\overline{D}$) *= 1.0.*

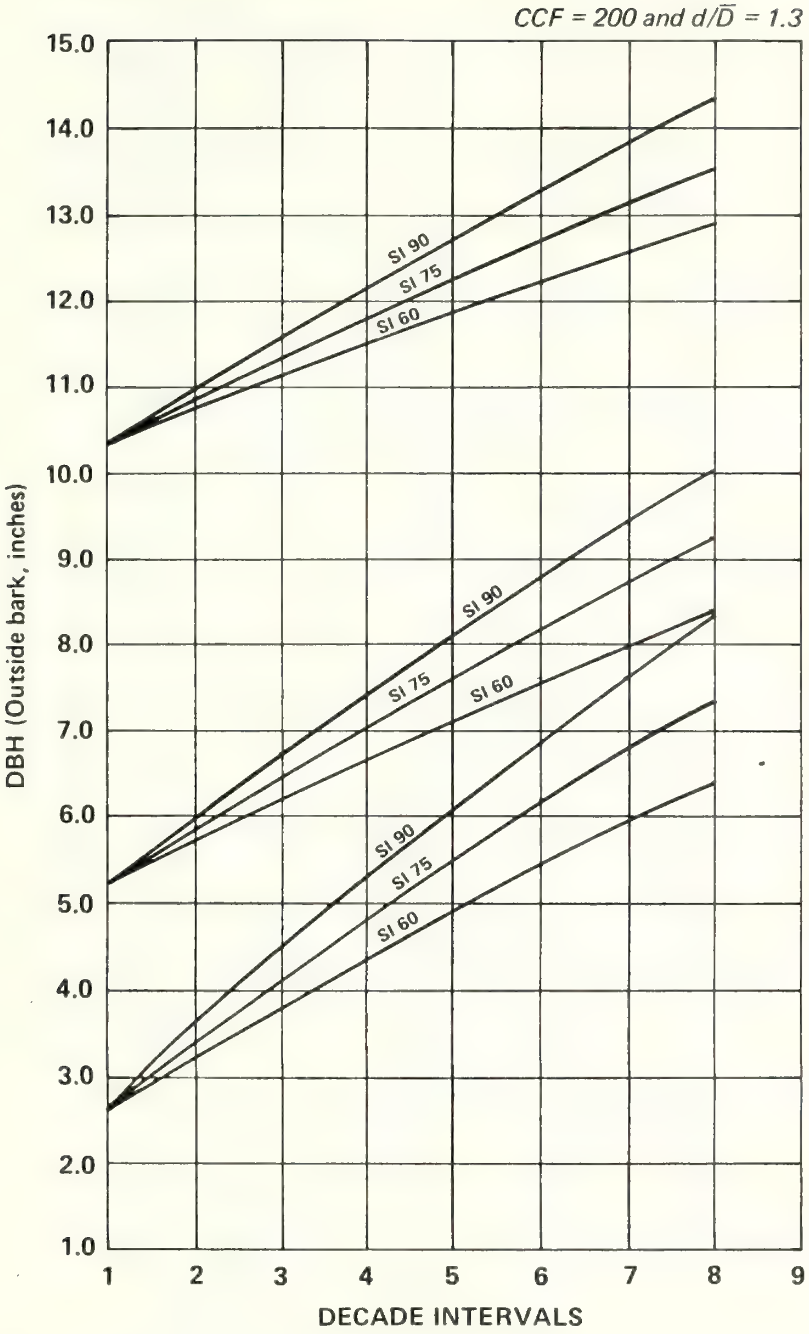
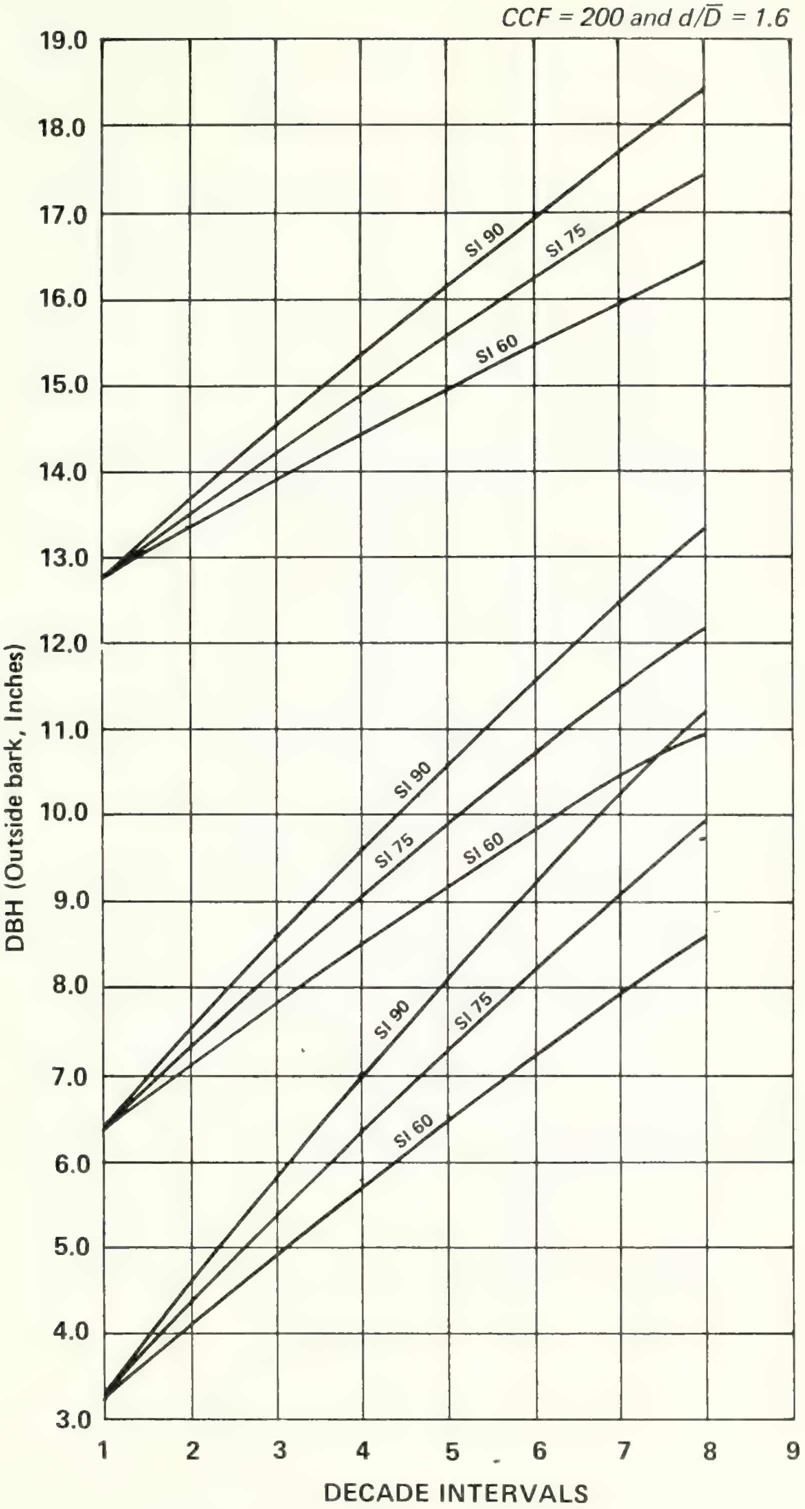


Figure 3b.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 200, and the ratio of tree d.b.h. to average stand d.b.h. (d/D̄) = 1.3.



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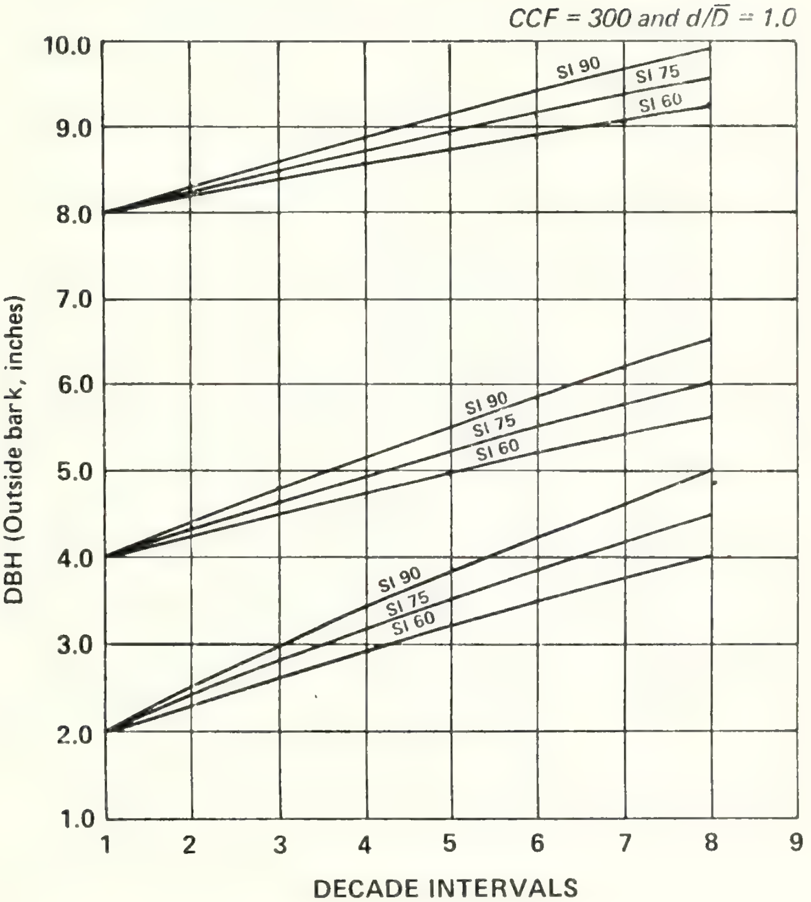

Figure 4a.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 300, and the ratio of tree d.b.h. to average stand d.b.h. ($d/\overline{D}$) = 1.0.

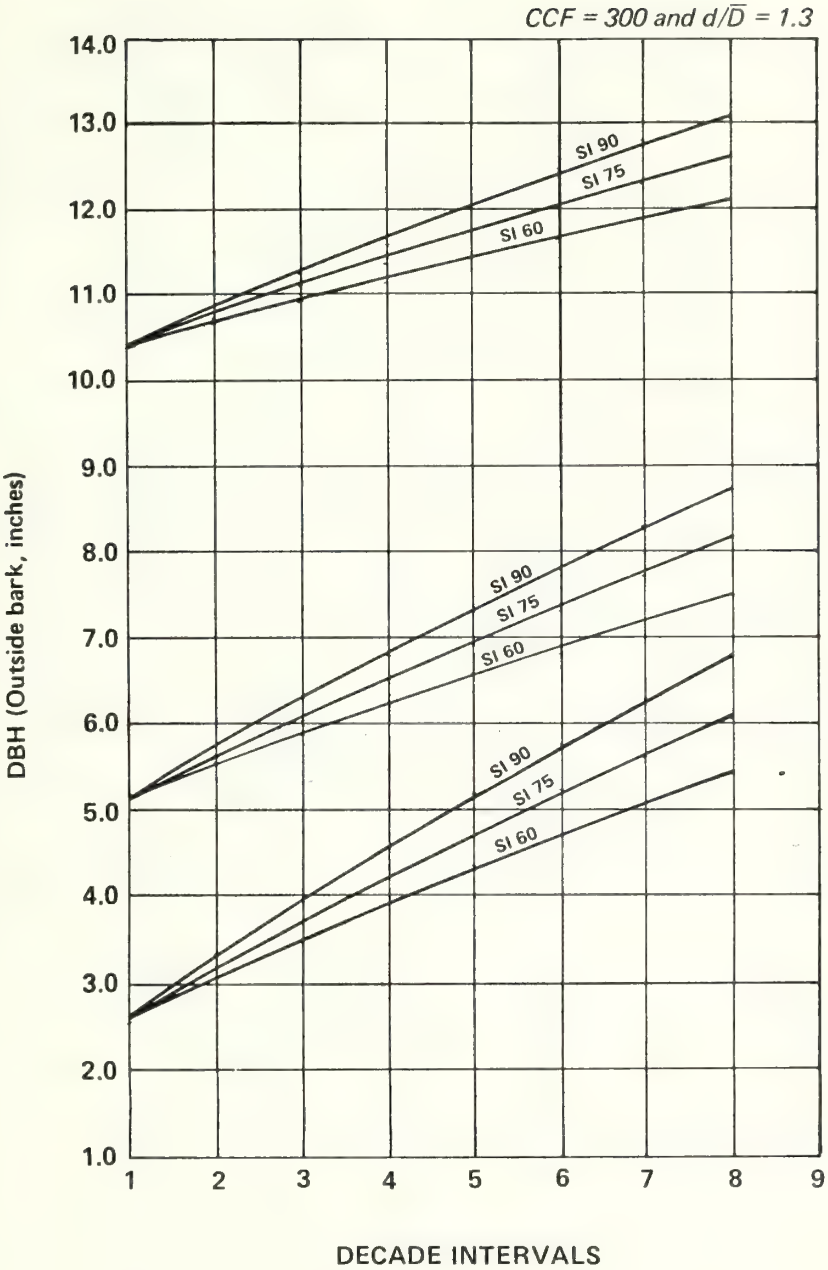

Figure 4b.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 300, and the ratio of tree d.b.h. to average stand d.b.h. (d/$\overline{D}$) = 1.3.

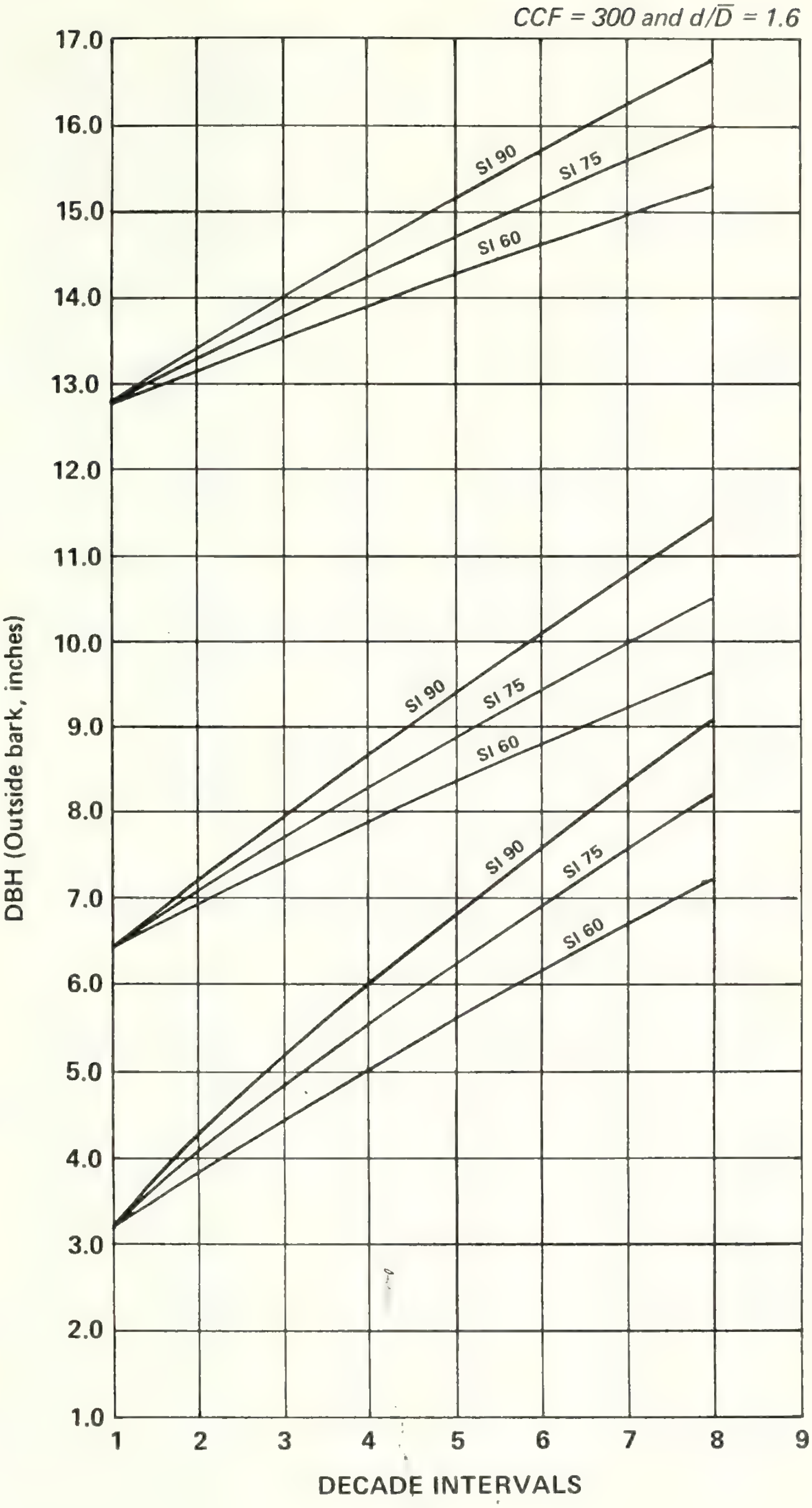

Figure 4c.--Diameter growth of individual lodgepole pine trees over 10-year intervals, by site index classes, for an average elevation of 6,000 feet--when Crown Competition Factor (CCF) = 300, and the ratio of tree d.b.h. to average stand d.b.h. $(d/\overline{D}) = 1.6$.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

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- Logan, Utah, (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
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